

# Comparison of wavelength-division-multiplexed distributed fiber Raman amplifier networks for sensors

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**Abstract:** A novel distributed fiber Raman amplified star topology used for optical sensor wavelength-division multiplexing is proposed. The performance of this star configuration is compared to an optically amplified bus topology. The two different network topologies are compared and demonstrated experimentally and theoretically as means of gathering information from four wavelength-division-multiplexed photonic sensors. We report how the star configuration yields better signal-to-noise ratios than the bus topology. Furthermore, this improvement is made without increasing the complexity of the regular star topologies.

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## References and links

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## 1. Introduction

Optical amplification has been one of the fastest growing optical technologies in the past decade. The performance of optical amplifiers keeps improving, increasing the bandwidth, gain, spectral response flatness, output power and reducing noise figures [1].

In a sensor environment, the main goal is to increase the number of sensors multiplexed in a single network, while keeping good quality of the signals. Sensor multiplexing networks have to deal with the problem of power losses due to the distribution scheme. Optical amplification is an alternative solution for the problem of poor power budgets, reducing splitting losses and highly increasing the number of sensors per fiber [2].

Nevertheless, the use of optical amplification raises the noise levels, which might limit the achievable signal to noise values on the sensors, losing precision, sensitivity and output range. For some amplifier configurations and network topologies, the maximum number of sensors might be determined by this degradation of signal to noise ratios, which reduces with the number of amplifiers.

Distributed amplification is particularly appealing, due to the need for a single pump source for all of the structure, reducing the network's cost and complexity. The application of distributed Raman amplification in long-haul, broadband transmission using wavelength division multiplexing (WDM) relies on the ability of the amplifiers to provide a flat gain profile to enable maximum reach of all signal channels [3-5]. The gain flatness of the amplifier over its operational bandwidth can be improved by using a large number of pumps [6]. In the case of Raman amplifiers it is possible to control the Raman gain profile, and so the Amplified Spontaneous Scattering (ASS) noise profile, which is the kind of noise that appears in Raman amplification.

In this paper we propose a novel fiber Raman amplifier star network that combines the use of Raman amplification and Fiber Bragg Gratings (FBGs) for WDM transmission over single-mode fiber. We compare this topology with a Raman bus structure. We demonstrate how the star configuration yields better signal-to-noise ratios than the bus topology, without increasing the complexity of the regular star networks.

## 2. Network configuration

In this section, a distributed fiber Raman amplified star topology used for optical sensor wavelength-division multiplexing is proposed. The performance of this star configuration is compared to an optically amplified bus topology.

In the bus topology there were used 90% directional couplers to perform power distribution among the sensors. In the star structure proposed there are used 3 dB couplers to divide the optical signal.

The bus topology is shown in Fig. 1(a), with an active bus built from standard single-mode fiber (ITU-G.652 compliant). It used wavelength-division multiplexing (WDM) for the identification of four sensors. Each sensor incorporates a narrow-bandwidth FBG at a unique wavelength. The launched signals are ultimately incident on all of the sensors but the gratings ensure that each sensor returns only its characteristic channel towards the launching point (the head end) after passing through the sensor a second time.

In all of our demonstrations, the sensors were removed in order to make the power measurements independent of the particular measurands and so ensure greater generality of the results. Therefore, although the gratings themselves may be utilized as sensors, the network is not designed to be specific to any particular type of sensor. The Raman pump laser used in both topologies was a multiwavelength laser and it radiated in three lines: 1428 nm, 1445 nm and 1466 nm. It could deliver up to 2 W power into the single-mode fiber. The signal was provided by a tunable laser (1460-1580 nm) and after passing through the launch circulator, it had a power of -2.6 dBm and a spectral linewidth of 5 MHz in both topologies.

In the bus network shown in Fig. 1(a), the Raman pump, signal(s) and receivers are co-

located in one head end. The Raman pump propagated co-directionally with the launched signal but contra-directionally with the reflected signals from the gratings. The couplers shown in Fig. 1 are all similar, having ratios of 90:10 at the pump and signal wavelengths. All of the free terminations on the bus are refractive-index-matched to frustrate unwanted reflections. This is necessary to minimize noise due to multi-path interference [7].

There is an initial span of 2.4 km of dispersion compensating fiber (DCF) added in both topologies. There are two benefits in doing this: to provide a means of compensating for accumulated dispersion of SMF and to achieve greater Raman gain per unit pump power. A novel scheme for a distributed fiber Raman amplified star topology used for optical sensor wavelength-division multiplexing is shown in Fig. 1(b).

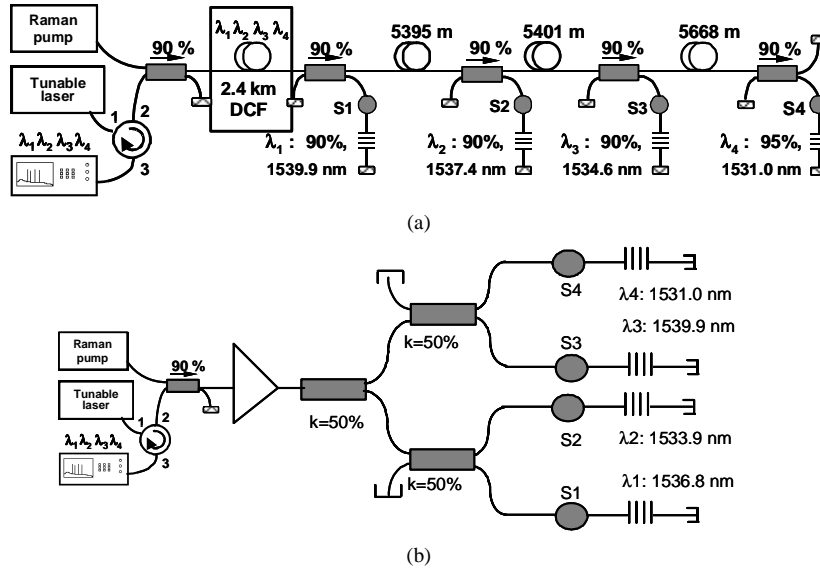


Fig. 1. (a) Wavelength-division-multiplexed distributed fiber Raman amplifier bus network. S1-S4 location of sensors. (b) Wavelength-division-multiplexed distributed fiber Raman amplifier star network. S1-S4 location of sensors. The fiber lengths and the grating peak wavelengths and reflectivities are indicated.

In the experimental setup shown in Fig. 1(b), 3 dB couplers are used to distribute the optical powers among the FBGs. The FBGs are employed to perform the selection of the operation wavelengths. The peak wavelengths are indicated on Fig. 1. All the gratings have 90% reflectivities. Two of the Fiber Bragg Gratings used in the new star configuration of Fig. 1(b), S1 and S2 are different from Fig. 1(a), because the new ones enable better equalization.

Optical power is thus divided into four branches of approximately equal power. A 90% coupler is used to extract 10% of the laser output power from the structure. As in the bus topology, all the free terminations on the star system have been immersed in refractive-index-matching gel to avoid undesired reflections that could destabilize the system.

The main drawback of this topology is the difficulty involved in expanding the number of channels in the structure. Increasing the number of channels would involve adding more couplers to the three already used, and therefore raising the losses by at least 6 dB. This increment in losses would reduce the system's efficiency. As an advantage, the FBGs are located in independent branches, thus individual channel attenuation control is straightforward.

### 3. Experimental results and discussion

In Fig. 1(a), S1... S4, show the position the sensors ought to take in the network. In the bus structure, a pump power of 270 mW is sufficient to obtain the transparency condition (constant optical power throughout the whole optical path). Figure 2(a) is a plot of the amplified output power obtained with an applied pump power of 270 mW.

It is very important to know the Raman gain profile corresponding to this pump power, in order to locate the FBGs. The strategy used to locate the FBGs is the following: The FBGs with wavelengths that correspond to low Raman gains in the Raman gain profile must be placed closest to the pump, because that is where the signals experience enough amplification. Conversely, gratings with relatively high Raman gains wavelengths must be located further from the head end. In the case of the star topology, the pump power necessary to obtain the transparency condition was 350 mW. Figure 2(b) is a plot of the amplified output power obtained with an applied pump power of 350 mW.

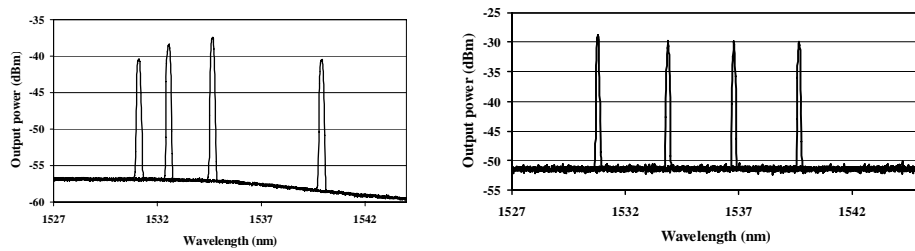


Fig. 2. (a) Amplified output power obtained for the bus topology with an applied pump power of 270 mW. The signal wavelengths are those of Figs. 1(a). 1(b) Amplified output power obtained for the star topology with an applied pump power of 350 mW. The signal wavelengths are those of Fig. 1(b).

According to the Raman gain profile, the sensors' location for the Fiber Bragg Gratings used in each configuration, as well as their corresponding optical signal to noise ratios (OSNR) considering the bus and the star setups of Fig. 1 are shown in Table 1.

Table 1. Measured values of power and optical signal to noise ratio obtained from Fig. 2.

	BUS TOPOLOGY				STAR TOPOLOGY			
	S1	S2	S3	S4	S1	S2	S3	S4
$\lambda$ (nm)	1539.9	1537.4	1534.6	1531.0	1536.8	1533.9	1539.9	1531.0
Pr (pumped), dBm	-39.96	-39.1	-39.67	-40.97	-29.9	-29.7	-30	-29.1
OSNR (pumped), dB	18.8	18.6	17.7	16.1	21.3	21.2	21.2	22.3

After doing some measurements, the best configuration to obtain power equalization is the one shown for the star topology in Table 1. The average signal power for the bus topology is -39.92 dBm, with a difference of 1.87 dB between extreme channels. The average OSNR values are close to 17.8 dB. In the star configuration there is a reduction in the noise level. This translates into an increment in the OSNR values, which turn out to be close to 21.5 dB. The power difference between channels has a maximum value of 0.9 dB.

## 4. Theoretical analysis

### 4.1 Bus topology

A typical scheme of the bus topology is shown in Fig. 1(a). In this configuration two problems arise, both of them related to the power losses on the structure: First, the necessary minimum detectable power at the receiver. The second problem is the dissimilar power received from each sensor due to the different number of directional couplers each one finds on its optical path. Within the sensor, two types of losses will be considered: excess losses ( $SL_{EX}$ ) and losses due to the intensity-modulated nature of the sensor ( $SL_{MOD}$ ), both of them accounting for double crossing through the sensor due to its reflective operation [7]. The lowest power will be received from sensor N and could be expressed as:

$$P_N = P_{IN} \cdot 0.1^2 \cdot k^2 \cdot (1-k)^{2N-2} \cdot \gamma^{2N+2} \cdot SL_{EX} \cdot SL_{MOD} \quad (1)$$

where k corresponds to the distribution coupler's coupling ratio and  $\gamma$  the excess loss:

$$\gamma = \frac{\sum_{k=1}^N P_{outk}}{P_{in}} \quad (2)$$

Maximizing Eq. (1), optimum coupling ratio can be obtained as  $k = 1/N$ . In bus topologies, distributed amplification is particularly appealing due to the need for a single pump source for the whole structure, reducing the network's cost and complexity. This distributed amplification yields a constant power in each sensor and a minor overall loss, therefore allowing a higher number of sensors to be multiplexed in each structure. With this kind of amplified architectures some hundreds of sensors could be multiplexed in a single structure.

The received optical power is defined as:

$$P_{OUT} = P_{IN} \cdot 0.1^2 \cdot \gamma^2 \cdot \frac{k^2}{(1-k)^2} \cdot SL_{EX} \cdot SL_{MOD} \quad (3)$$

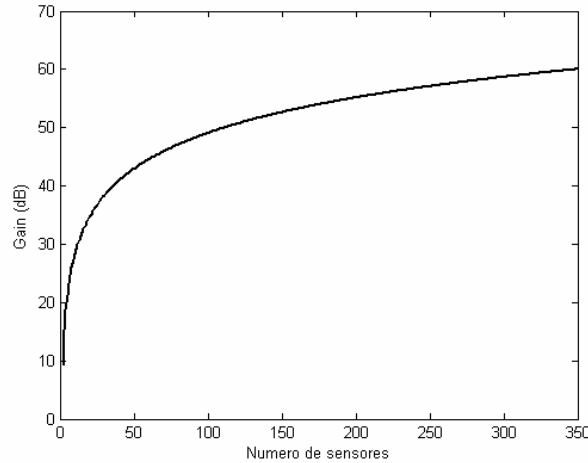


Fig. 3. Variation of the gain with the number of sensors in a bus network ( $SL_{EX} = 1$  dB,  $SL_{MOD} = 10$  dB,  $\gamma = 0.98$ ).

Using  $k=1/N$  (optimum value of  $k$ ) and as the gain is the ratio  $P_{OUT}/P_{IN}$ , the variation of the gain with the number of sensors is obtained in Fig. 3. There were used the specifications corresponding to the network's sensors of Fig. 1(a):  $SL_{EX} = 1$  dB,  $SL_{MOD} = 10$  dB and  $\gamma = 0.98$ . As shown in Fig. 3, with this kind of amplified architectures some hundreds of sensors could be multiplexed in a single structure.

#### 4.2 Star topology

In the star network, the detected power at the receiver in the optimum case will have to account for distribution and sensor losses. In this case, there are used 2x2 couplers in the setup of Fig. 1(b), so that they introduce 3 dB losses. From these considerations and having a  $P_{IN}$  input power, the network output power would be equal for all the sensors in the network and could be expressed as:

$$P_{OUT} = \frac{P_{IN} \cdot SL_{EX} \cdot SL_{MOD} \cdot \gamma^2}{N^2} \quad (4)$$

From the specifications of the experimental network of Fig. 1(b),  $P_{IN} = -10$  dBm,  $SL_{EX} = 1$  dB,  $SL_{MOD} = 10$  dB and  $\gamma = 0.98$ . With a minimum detectable power  $P_{MDP}$  at the receiver, the maximum number of sensors addressed in a star network would equal:

$$N = \sqrt{\frac{P_{IN} \cdot SL_{EX} \cdot SL_{MOD}}{P_{MDP}}} \cdot \gamma \quad (5)$$

In the setup shown in Fig. 1(b), optical amplification in the form of a postamplifier of gain  $G$  is included right after the source, so that  $P_{IN}$  should be substituted by  $P_{IN} \cdot G$ . In order to multiplex  $N$  sensors and from Eq. (5) a necessary gain value  $G$  would be:

$$G = \left(\frac{N}{\gamma}\right)^2 \frac{P_{MDP}}{P_{IN} \cdot SL_{EX} \cdot SL_{MOD}} \quad (6)$$

The use of optical amplification within the network also introduces noise power. Thus, a fundamental design parameter is the noise figure of the whole system, defined as:

$$F = \frac{SNR_{in}}{SNR_{out}} \quad (7)$$

$SNR_{in}$  and  $SNR_{out}$  being the input and output signal-to-noise ratios respectively, being the latter close related to the worst sensor in the structure. Fig. 4(a) shows the variation of the maximum number of sensors multiplexed in a star network as  $G$  ranges from 0 to 20 dB. The variation of  $F$  over the considered  $N$  range is shown in Fig. 4(b).

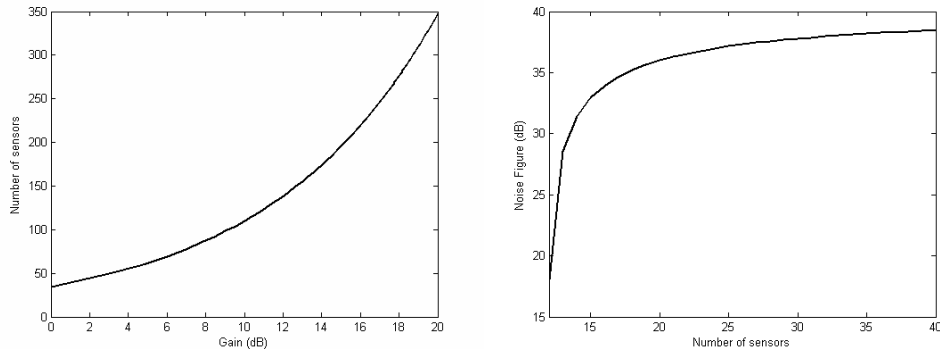


Fig. 4. (a). Maximum number of sensors in an active star network with postamplifier ( $P_{IN} = -10$  dBm,  $P_{MDP} = -50$  dBm,  $SL_{EX} = 1$  dB,  $SL_{MOD} = 10$  dB,  $\gamma = 0.98$ ). (b) Noise figure of an active star network with postamplifier.

As shown in Fig. 4(a), the inclusion of the amplifier rapidly increases the number of sensors multiplexed. The inclusion of optical amplifiers can counterbalance the structure losses, yielding a constant power at the receiver as  $N$  increases, and therefore improving  $F$ , as shown in Fig. 4(b). By employing power amplifiers, system noise figures under 40 dB can be obtained in a star network with 300 sensors.

## 7. Conclusions

We have demonstrated a novel distributed Raman amplifying star network for wavelength division multiplexing of sensors. Each sensor is identified by a fiber Bragg grating. This scheme has been compared to an optically amplified bus topology. This new structure yields better signal-to-noise ratios than the bus configuration, without increasing the complexity of the regular star topologies. This improvement is achieved by using only 350 mW Raman pump power. As the sensors are located in independent branches, individual channel attenuation control is straightforward.

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